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A reference atmosphere for the Indian equatorial zone

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An empirical reference atmospheric model applicable to 0-15°N latitude and 0-80 km height range in the Indian equatorial zone is constructed from the balloon and rocket data obtained at Trivandrum for a period of 16 years. The reference atmospheric temperatures are compared with those of CIRA 1986 for 10°N latitude (*Cospar International Reference Atmosphere*: 1986—*Part II: Middle Atmosphere Models*, edited by D Rees, J J Barnett and K Labitzke (Pergamon Press, Oxford), 1990) and significant differences between the two are found at mesospheric altitudes. The possible reasons for the same are discussed.

1 Introduction

The thermal structure of the middle atmosphere is very important for many technical and scientific studies. For instance, for launching of sounding rockets and satellite launch vehicles the vertical distribution of the atmospheric temperature, density and pressure is an important input. Similarly for scientific studies such as the study of propagation of waves (e.g. tides, Kelvin waves, mixed Rossby-gravity waves and gravity waves) through the earth's atmosphere, knowledge of the atmospheric parameters, namely, temperature and density, is necessary.

A few empirical reference models of the atmospheric parameters are available for the equatorial region with incorporation of limited spatial and temporal variations. For example, CIRA 1972 (Ref. 1) and Cole and Kantor[2] give the vertical distribution of temperature, pressure and density in the eqatorial middle atmosphere at 0°N and 10°N/15°N at 5-km height intervals and for every month. These empirical reference models are essentially based on the Meteorological Rocket Network (MRN) data from stations located in the longitude range of 14°W to 160°W, with relatively few measurements in the equatorial region. Since the preparation of CIRA 1972 (Ref. 1), there has been a substantial increase in the number of measurements of atmospheric thermal structure by different satellite experiments as well as by meteorological rockets and different ground-based techniques.

Recently, a draft of the new "Reference Atmosphere for the Middle Atmosphere" based on satellite-derived temperature data has been proposed by Barnett and Corney[3]. This proposed reference atmosphere is based on infrared radiance data obtained by Selective Chopper Radiometer (SCR) aboard Nimbus 5 satellite during January 1973-December 1974 and by Pressure Modulator Radiometer (PMR) aboard Nimbus 6 during June 1975-July 1978. This reference atmosphere makes use of climatology derived by Oort[4] below about 20 km and gives the monthly zonal mean temperature, pressure and density in the height range 0-80 km at 5-km intervals from 80°S to 80°N latitude in 10° latitude steps and this has become part of CIRA 1986 (Ref. 5). Apart from the satellite data based middle atmosphere reference atmosphere by Barnett and Corney[3], Koshelkov[6] proposed a middle atmosphere reference model for the Southern Hemisphere derived exclusively from rocketsonde data. Koshelkov gives the monthly mean thermodynamic variables (temperature, pressure and density) in the 25-80 km height range at every 5 km and 0°-70°S latitude in steps of 10°. Ananthasayanam and Narasimha[7] proposed an international tropical reference atmosphere up to 80 km, based on balloonsonde, rocketsonde and grenade and falling sphere data, valid for the tropical region up to 30° from the equator.

WMO (World Meteorological Organization) defines (as given in CIRA 1972) a standard atmosphere as a hypothetical vertical distribution of atmospheric temperature, pressure and density which, by international agreement, is roughly representative of year-round, mid-latitude conditions, and a reference atmosphere as a family of atmos-

pheres which are hypothetical vertical distributions of atmospheric temperature, pressure and density which, by international agreement, are roughly representative of the various geographical and seasonal conditions over the earth. The tropical reference atmosphere by Ananthasayanam and Narasimha[7] gives a single vertical distribution of temperature, pressure and density for annual mean conditions and for the entire tropical region from 0 to 30°N and hence their 'reference' atmosphere can really be only a 'standard' atmosphere.

In addition to the zonal mean reference atmospheres in the 0-80 km mentioned earlier, Justus *et al.*[8,9] had developed a four-dimensional (4-D) global reference atmospheric model for surface to orbital heights which was later revised by Justus *et al.*[10] This 4-D global reference atmospheric model can generate (using a computer program) thermodynamical variables and winds as a function of height (0-700 km), latitude, longitude and time (month) and is based on radiosonde, rocketsonde, and satellite data. This model also can give perturbations about the monthly means and quasi-biennial oscillations. These perturbations partially simulate the variability due to synoptic, diurnal, planetary wave and gravity wave variations.

One essential input in the development of reference models such as those of CIRA 1986 (Ref. 5), Barnett and Corney[3], Koshelkov[6] and Justus *et al.*[10] is the reference atmospheres over stations spread over different latitudes and longitudes all over the globe. Further, for the revision of these reference models or for the retrieval of atmospheric temperatures from satellite radiance data, the reference atmospheres at particular locations are necessary, especially when they are used as initial guess of the temperature profile in the temperature retrieval from radiance data. The importance of the reference atmospheres at individual stations in the tropical region is enhanced in the light of recent reports of planetary scale features in the tropical mesospheric temperature (e.g. Barnett and Corney[11], Venne *et al.*[12]) and large longitudinal variation of temperature (~ 20 K) in the equatorial mesosphere (Clancy and Rusch[13]).

Sasi and Sen Gupta[14] have proposed a reference atmosphere for the low-latitude Indian zone which gives the vertical distribution of temperature, density and pressure at 1-km intervals in the 0-80 km height range for every month. Their reference model is based on temperature data at Trivandrum in the 0-80 km altitude range for the period January 1971 to April 1982. It gives annual means and monthly mean values of temperature, pressure and density at every km altitude from 0 to 80 km. In this paper this reference atmosphere for the Indian equatorial zone from surface to 80 km is revised using meteorological balloon data and M-100/M-100B rocket data at Trivandrum (8.5°N, 77°E) from December 1970 to November 1986. Though the reference atmosphere is based on data only at Trivandrum, it may be valid for the latitude range 0°-15°N in the equatorial Indian zone since the latitudinal variations in the atmospheric thermodynamic variables are small within 15° of the equator[2].

2 Data

The temperature data used for evolving the reference atmosphere are based on meteorological balloon data in the 0-23 km height range and M-100/M-100B rocket data in the 24-80 km height range at Trivandrum. Differences exist between the radiosonde and rocketsonde temperatures for individual flights in the lower stratosphere (in the overlapping height region) and they are essentially random in nature. The differences between the corresponding monthly mean values get considerably reduced. Hence modification of temperature values was not necessary in this height region. The total length of the data is 16 years from December 1970 to November 1986 with a gap of 11 months from June 1974 to April 1975. Using spline interpolation method, the data are interpolated for these gap periods.

The temperatures measured by balloonsonde have errors (r.m.s.) of ~ 1 K. The r.m.s. errors in the rocket-measured (M-100B) temperatures were experimentally determined by Lysenko *et al.*[15] and vary from 2.7 K at 20 km to 11 K at 80 km. In addition to the r.m.s. errors in the temperatures measured by M-100/M-100B rockets, these temperatures contain systematic errors as noted in an international experiment (Finger and Gelman[16]; Finger *et al.*[17]). This experiment was conducted to determine the compatibility of temperature values as measured with different types of sensors in rocket payloads by different countries. In this experiment, conducted at Guiana, four countries, France, UK, USSR and USA, participated. The results indicated, in general, good compatibility among temperature values as obtained with different sensors below 40 km. Above that level, different sensors gave different temperature values. In the above experiment, temperature sensors of USSR, UK and France were wire-type whereas that of USA was bead-type thermistor.

The results of this experiment showed that the average differences in temperatures measured by these four payloads up to about 45 km remain well within ±5 K, with no systematic bias apparent. Above 45 km, French, UK and USA measurements were found to give generally compatible values, despite occasional mean differences larger than 5 K (which may be considered random in nature). However, the average differences of temperatures as measured with the USSR payload were found to increase steadily above 45 km, reaching approximately 20 K between 60 and 65 km and then decreasing with height above 65 km.

Subsequently, there was one more intercomparison experiment held in 1977 at Wallops Island in which USA and USSR participated. It was found from this experiment that the temperature payloads used by the USA and USSR yielded different temperature profiles (Ivanovsky *et al.*[18], Schmidlin[19]). These differences were systematic and were attributed to the differences in the method of measuring temperature and in the data processing procedures. Following this intercomparison experiment there was a change in M-100B rocket payload since January 1978 (Koshelkov *et al.*[20]). The change in payload led to changes in the data processing. As a result of these changes, since January 1978 the M-100B rocket-measured temperature data as published by Central Aerological Observatory, Moscow, seem to be free from any kind of systematic biases unlike in the published data prior to December 1977. Recent studies made on temperature variations in the equatorial atmosphere by Koshelkov *et al.*[20] and on the thermal structure of the Southern Hemisphere by Koshelkov[6] show that the mesospheric temperatures as obtained by M-100/M-100B rockets prior to December 1977 and published from Moscow need to be adjusted for compatibility with the temperature data from January 1978. Following Koshelkov *et al.*[20], these adjustment factors were obtained from the differences of the mean (in time) temperatures at each kilometre height above 50 km, before and after January 1978 and are shown in Fig. 1 and these are applied to the temperature data up to December 1977 (prior to January 1978). The temperature data from January 1978 have been taken as such without any adjustments. A similar procedure was adopted by Sasi and Sen Gupta[14] for evolving their reference atmosphere.

3 Method of analysis

The weekly values of temperatures from M-100/M-100B rocket and meteorological balloon observations were averaged over a period of one month to obtain monthly mean values at every kilometre height. This process was repeated for each month for the 16-year period from December 1970 to November 1986. The missing monthly mean values were interpolated using spline approximation. Thus a total of 192 monthly means of temperatures were available for the analysis.

The monthly mean temperature data were subjected to spectrum analysis using Fast Fourier Transform (FFT) technique. Using the long-term mean (considered as the average annual mean) and the amplitudes and phases of the annual, semiannual and terannual components, obtained from the FFT analysis, and Eq. (1) given below, the average monthly mean values (12) were generated at every kilometre height and these monthly mean values of the temperature constitute the reference model atmosphere (temperature) for the Indian equatorial zone.

$$\bar{A}(t) = \bar{A}_0 + \bar{A}_1 \cos(\omega t - \bar{\phi}_1) + \bar{A}_2 \cos(2\omega t - \bar{\phi}_2) + \bar{A}_3 \cos(3\omega t - \bar{\phi}_3) \quad \ldots (1)$$

where

$\bar{A}(t)$ Temperature at time t

$\bar{A}_0$ Annual mean temperature (over 16 years)

$\bar{A}_1, \bar{A}_2, \bar{A}_3$ Amplitudes of the annual, semiannual and terannual oscillations respectively (over 16 years)

$\bar{\phi}_1, \bar{\phi}_2, \bar{\phi}_3$ Phases of the annual, semiannual and terannual oscillations respectively (over 16 years)

$\omega = 2\pi/\tau$

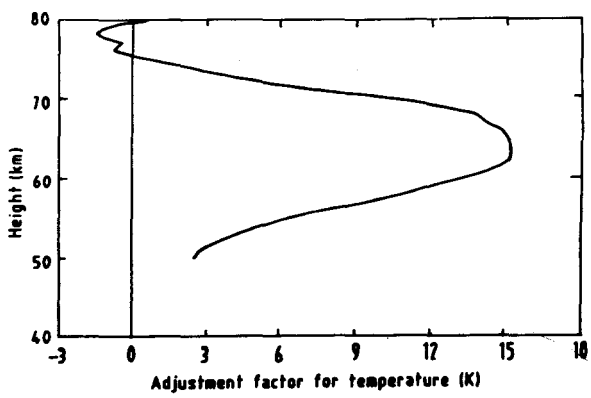

Fig. 1—Adjustment factors for M-100 rocket-measured temperatures in the 40-80 km height range.

where

$\tau = 12$ months, the annual period

$t = 0,1,2, ..., 11$, where 0,1,2, ..., 11 corresponds to the middle of December, January, ..., November respectively

$\bar{A}_0$, $\bar{A}_1$, $\bar{A}_2$, $\bar{A}_3$, $\bar{\phi}_1$, $\bar{\phi}_2$ and $\bar{\phi}_3$ in Eq. (1) are the long-term (over 16 years) mean values and these values are given in Table 1.

The height profiles of monthly mean temperatures for the months of January, April, July and October generated using the values of $\bar{A}_0$, $\bar{A}_1$, $\bar{A}_2$, $\bar{A}_3$, $\bar{\phi}_1$, $\bar{\phi}_2$ and $\bar{\phi}_3$ from Table 1 and Eq. (1) are given in Fig. 2. It is seen from Fig. 2 that seasonal variations are siginificant in the entire height range 0-80 km. Since the seasonal variation in temperatures is small and the temperature lapse rates are large in the troposphere, seasonal variation is partially masked and is not as conspicuous as in the stratosphere and mesosphere. It can be seen from Fig. 2 that seasonal variation in temperature is relatively high in the upper stratosphere and upper mesosphere.

In the tropical stratosphere the seasonal variation of temperature is mainly produced by the ozone heating by the semiannually varying solar ultraviolet flux and the maximum ozone heating takes place in the upper stratosphere around equinox times. In the tropical mesosphere seasonal

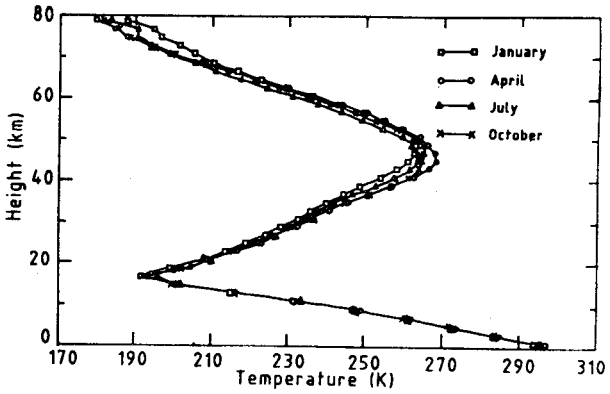

Fig. 2—Average (16-year) seasonal variation of temperature at Trivandrum (8.5°N, 77°E).

variation in temperature is partially produced by semiannually varying adiabatic expansion induced by the semiannual ozone heating in the upper stratosphere and the maximum adiabatic cooling may be expected to take place just below the mesopause level. Further, seasonal dependence of the breaking up of gravity waves and tides in the upper mesosphere and the consequent temperature changes taking place there will result in a large seasonal variation of temperature in this region. Thus one can expect seasonal variation in temperature to be relatively large in the upper stratosphere and upper mesosphere.

Table 1—Annual mean temperature ($\bar{A}_0$) and amplitudes and phases of the annual (AO), semiannual (SAO) and terannual (TAO) oscillations of temperatures at Trivandrum and their standard deviations (year-to-year variability) (standard deviations are shown in parentheses)

Height km	$\bar{A}_0$ K	$\bar{A}_1$ K	$\bar{\phi}_1$ deg	$\bar{A}_2$ K	$\bar{\phi}_2$ deg	$\bar{A}_3$ K	$\bar{\phi}_3$ deg
0	303.53	2.14	72.07	1.02	239.75	.34	24.43
	(.5)	(.3)	(6.6)	(.3)	(13.7)	(.2)	(120.4)
1	294.93	1.18	94.36	.50	234.91	.14	74.52
	(.9)	(.9)	(44.4)	(.4)	(65.0)	(.5)	(100.4)
2	288.76	.91	115.31	.53	244.32	.18	39.52
	(.7)	(.6)	(48.1)	(.5)	(76.9)	(.3)	(124.1)
3	283.97	.72	105.53	.22	254.30	.23	61.47
	(.5)	(.5)	(46.0)	(.3)	(93.5)	(.3)	(107.1)
4	278.36	.38	106.10	.17	259.68	.03	42.40
	(.9)	(1.0)	(93.0)	(.3)	(87.3)	(.3)	(100.9)
5	272.88	.34	118.87	.17	237.22	.13	2.31
	(.9)	(1.1)	(92.0)	(.3)	(92.6)	(.4)	(109.2)
6	267.15	.41	185.24	.35	298.96	.25	51.12
	(1.1)	(1.3)	(85.9)	(.5)	(81.5)	(.5)	(105.7)
7	261.38	.39	165.52	.51	303.22	.26	60.28
	(1.1)	(1.2)	(80.6)	(.4)	(83.1)	(.3)	(90.4)
8	255.02	.56	184.53	.58	302.78	.16	65.25
	(1.0)	(1.1)	(71.4)	(.3)	(67.7)	(.5)	(99.2)

Contd.

Table 1—Annual mean temperature ($\bar{A}_0$) and amplitudes and phases of the annual (AO), semiannual (SAO) and terannual (TAO) oscillations of temperatures at Trivandrum and their standard deviations (year-to-year variability) (standard deviations are shown in parentheses)—(*Contd*)

Height km	$\bar{A}_0$ K	$\bar{A}_1$ K	$\bar{\phi}_1$ deg	$\bar{A}_2$ K	$\bar{\phi}_2$ deg	A_3 K	ϕ_3 deg
9	248.12	.76	181.68	.94	294.47	.32	75.42
	(1.2)	(1.0)	(64.2)	(.7)	(62.7)	(.6)	(102.8)
10	240.42	.52	201.36	.62	248.67	.15	138.56
	(1.6)	(1.1)	(74.2)	(1.0)	(64.2)	(.7)	(105.8)
11	232.47	.64	183.94	.90	299.83	.15	51.95
	(1.4)	(1.0)	(79.4)	(.4)	(47.2)	(.3)	(110.0)
12	224.08	.78	174.99	.87	302.25	.23	67.44
	(1.4)	(.9)	(69.5)	(.6)	(78.6)	(.4)	(99.5)
13	215.91	.89	180.08	.83	302.87	.11	82.41
	(1.4)	(.7)	(74.6)	(.7)	(96.7)	(.4)	(110.0)
14	207.78	.92	144.24	.48	304.33	.08	126.72
	(1.5)	(.7)	(77.1)	(.6)	(97.3)	(.5)	(92.6)
15	200.78	.65	97.63	.18	236.20	.13	246.74
	(1.5)	(.7)	(89.7)	(.4)	(89.2)	(.3)	(106.2)
16	195.78	.32	284.35	.57	138.12	.14	218.27
	(1.2)	(.7)	(89.3)	(.5)	(75.6)	(.5)	(104.9)
17	193.72	1.81	248.43	1.30	111.99	.24	181.26
	(1.6)	(.8)	(68.2)	(.6)	(37.7)	(.5)	(82.7)
18	197.00	3.21	247.30	1.27	107.53	.13	183.28
	(2.3)	(1.5)	(69.7)	(.8)	(41.2)	(.6)	(90.5)
19	201.61	3.07	244.06	.71	93.78	.09	76.61
	(2.0)	(1.9)	(48.9)	(1.0)	(82.5)	(.8)	(89.4)
20	206.35	2.08	251.76	.33	30.55	.44	35.60
	(1.5)	(1.5)	(70.5)	(.8)	(111.1)	(.6)	(104.3)
21	209.97	.89	253.86	.28	13.06	.10	91.77
	(1.6)	(1.0)	(89.6)	(.9)	(109.7)	(1.1)	(120.4)
22	212.62	1.20	207.92	.24	351.86	.29	328.90
	(2.1)	(1.0)	(58.0)	(.9)	(109.3)	(.4)	(118.7)
23	215.75	1.43	195.55	.72	306.66	.11	285.30
	(2.0)	(1.0)	(45.5)	(.8)	(93.6)	(.5)	(90.0)
24	218.63	2.02	201.29	.81	339.63	.16	215.32
	(1.7)	(1.5)	(42.9)	(.8)	(138.5)	(.6)	(98.3)
25	221.35	1.87	200.46	.89	326.81	.25	316.87
	(1.6)	(1.4)	(54.3)	(.7)	(129.7)	(.4)	(117.2)
26	223.84	1.78	204.24	1.05	329.40	.33	322.22
	(1.3)	(1.3)	(51.6)	(.7)	(123.3)	(.4)	(119.8)
27	226.10	1.28	199.71	1.20	329.25	.28	333.72
	(1.3)	(1.3)	(66.2)	(.7)	(121.0)	(.7)	(95.9)
28	228.18	1.42	189.67	1.46	307.77	.41	311.39
	(1.2)	(1.0)	(58.9)	(.7)	(100.5)	(.5)	(116.1)
29	230.38	1.05	158.80	1.43	292.92	.60	303.66
	(1.3)	(.9)	(67.9)	(.7)	(74.9)	(.5)	(92.6)
30	232.82	.52	121.28	1.59	277.49	.57	284.54
	(1.7)	(1.6)	(83.6)	(.9)	(68.7)	(.6)	(99.5)
31	234.79	.30	96.12	1.68	266.26	.62	254.86
	(1.7)	(1.3)	(91.1)	(1.0)	(41.7)	(.6)	(80.5)
32	236.34	.30	78.87	2.09	264.91	.44	259.79
	(1.3)	(.9)	(97.5)	(1.1)	(30.7)	(.7)	(107.3)

Contd.

Table 1—Annual mean temperature ($\bar{A}_0$) and amplitudes and phases of the annual (AO), semiannual (SAO) and terannual (TAO) oscillations of temperatures at Trivandrum and their standard deviations (year-to-year variability) (standard deviations are shown in parentheses)—(*Contd*)

Height km	$\bar{A}_0$ K	$\bar{A}_1$ K	$\bar{\phi}_1$ deg	$\bar{A}_2$ K	$\bar{\phi}_2$ deg	$\bar{A}_3$ K	$\bar{\phi}_3$ deg
33	238.31	.20	81.60	2.22	265.14	.68	268.51
	(1.3)	(1.0)	(105.4)	(.9)	(28.3)	(.7)	(88.8)
34	240.80	.06	112.11	2.45	265.67	.64	261.76
	(1.3)	(.7)	(101.4)	(.9)	(24.7)	(.7)	(88.2)
35	243.29	.13	216.76	2.61	261.06	.57	251.47
	(1.4)	(.7)	(100.8)	(1.2)	(32.7)	(.9)	(87.4)
36	245.77	.26	202.91	2.76	255.62	.41	255.04
	(1.6)	(.9)	(104.2)	(1.3)	(66.0)	(1.0)	(104.7)
37	248.36	.78	198.60	2.89	258.20	.42	235.68
	(1.8)	(1.1)	(91.2)	(1.2)	(23.6)	(.9)	(99.8)
38	251.06	1.34	198.61	3.08	258.40	.64	230.91
	(2.0)	(1.3)	(66.6)	(1.1)	(21.6)	(.8)	(88.0)
39	253.71	1.36	197.01	3.17	253.74	.68	237.23
	(2.2)	(1.2)	(63.9)	(1.4)	(20.4)	(.7)	(77.1)
40	256.40	1.17	183.32	3.18	246.18	.70	240.16
	(2.5)	(1.0)	(75.9)	(1.5)	(22.7)	(.6)	(74.6)
41	258.70	1.15	161.87	3.00	238.00	.91	258.83
	(2.4)	(.8)	(72.4)	(1.5)	(27.9)	(.6)	(84.5)
42	260.62	1.24	137.11	2.73	231.59	1.00	273.34
	(2.2)	(1.0)	(84.2)	(1.3)	(27.1)	(.8)	(90.7)
43	262.36	1.31	139.05	2.58	223.02	1.10	276.69
	(2.0)	(1.1)	(69.4)	(1.4)	(25.6)	(.9)	(82.5)
44	263.58	1.62	127.58	2.32	218.74	1.05	278.84
	(1.9)	(1.1)	(65.9)	(1.2)	(30.8)	(.9)	(88.6)
45	264.23	1.78	120.58	2.18	217.16	1.04	277.36
	(1.9)	(1.2)	(64.8)	(1.1)	(32.4)	(.9)	(76.6)
46	264.64	1.74	114.74	2.06	211.95	1.12	272.02
	(1.8)	(1.2)	(80.2)	(1.2)	(31.8)	(.9)	(96.1)
47	264.58	1.74	98.93	1.96	207.82	.92	260.24
	(2.2)	(1.8)	(82.6)	(1.1)	(38.3)	(.9)	(81.1)
48	264.57	1.34	90.96	1.73	204.04	.84	239.06
	(1.9)	(1.3)	(85.8)	(1.0)	(45.4)	(.8)	(90.8)
49	263.92	1.29	80.68	1.75	197.36	.61	221.31
	(2.2)	(1.4)	(85.7)	(1.0)	(40.0)	(.8)	(91.6)
50	263.76	1.50	65.07	1.66	194.47	.50	195.12
	(2.1)	(1.6)	(89.3)	(1.0)	(44.7)	(.9)	(89.0)
51	262.04	1.55	60.92	1.44	201.72	.26	136.89
	(2.4)	(1.8)	(92.8)	(.9)	(50.5)	(1.1)	(103.2)
52	260.03	2.10	56.94	1.49	199.80	.81	119.95
	(2.6)	(2.1)	(105.1)	(1.0)	(59.1)	(1.2)	(85.6)
53	257.86	2.03	62.26	1.26	196.24	.82	116.36
	(2.9)	(2.0)	(100.4)	(.9)	(64.7)	(1.1)	(90.8)
54	255.41	2.14	58.50	1.21	196.66	.91	112.92
	(2.9)	(1.9)	(102.6)	(.9)	(64.0)	(1.1)	(90.3)
55	252.67	2.34	56.59	1.18	192.96	.80	107.54
	(2.8)	(1.8)	(92.4)	(.8)	(65.7)	(.9)	(89.4)
56	250.13	2.63	55.45	1.22	192.08	.61	99.85

Contd.

Table 1—Annual mean temperature ($\bar{A}_0$) and amplitudes and phases of the annual (AO), semiannual (SAO) and terannual (TAO) oscillations of temperatures at Trivandrum and their standard deviations (year-to-year variability) (standard deviations are shown in parentheses)—(*Contd*)

Height km	$\bar{A}_0$ K	$\bar{A}_1$ K	$\bar{\phi}_1$ deg	$\bar{A}_2$ K	$\bar{\phi}_2$ deg	$\bar{A}_3$ K	$\bar{\phi}_3$ deg
	(2.9)	(2.0)	(92.1)	(.9)	(62.2)	(.8)	(105.5)
57	247.50	2.88	55.64	1.47	191.32	.47	111.54
	(2.9)	(2.4)	(89.2)	(1.0)	(55.0)	(1.1)	(105.5)
58	244.40	3.01	55.61	1.62	181.88	.22	42.82
	(2.7)	(2.1)	(85.8)	(1.0)	(52.4)	(.6)	(106.3)
59	241.20	3.14	52.19	1.79	180.17	.22	326.29
	(2.5)	(1.8)	(95.8)	(1.0)	(46.7)	(.7)	(102.4)
60	237.93	3.28	48.10	1.98	179.84	.55	294.23
	(2.4)	(1.9)	(98.7)	(.9)	(43.0)	(.7)	(96.6)
61	234.58	3.35	44.52	2.19	180.69	.84	279.90
	(2.6)	(1.9)	(102.4)	(.9)	(42.4)	(.8)	(95.9)
62	231.17	3.59	43.30	2.35	173.50	1.10	280.15
	(2.7)	(2.1)	(98.7)	(.9)	(43.2)	(.9)	(98.7)
63	227.74	3.91	39.59	2.45	172.88	1.46	281.54
	(2.8)	(2.3)	(96.6)	(1.0)	(41.2)	(1.0)	(86.8)
64	224.35	4.13	37.14	2.55	168.67	1.45	277.18
	(2.8)	(2.5)	(112.1)	(1.1)	(35.3)	(1.0)	(67.9)
65	221.05	4.24	36.73	2.45	167.37	1.55	279.92
	(2.8)	(2.7)	(113.1)	(1.1)	(41.8)	(1.1)	(67.8)
66	217.65	4.51	35.13	2.43	164.11	1.71	279.10
	(2.6)	(2.8)	(100.1)	(1.3)	(40.0)	(1.2)	(67.8)
67	214.15	4.65	33.24	2.38	157.47	1.77	277.15
	(2.4)	(2.9)	(70.0)	(1.3)	(41.9)	(1.4)	(71.7)
68	210.69	4.48	32.56	2.17	152.54	1.87	273.99
	(2.2)	(2.9)	(95.4)	(1.2)	(57.8)	(1.4)	(89.1)
69	207.45	4.32	31.80	2.13	133.9	2.01	276.41
	(2.0)	(2.7)	(95.1)	(1.2)	(69.7)	(1.6)	(93.8)
70	203.98	4.76	29.56	2.10	128.33	1.76	280.90
	(2.2)	(2.9)	(95.7)	(1.3)	(60.0)	(1.2)	(89.4)
71	200.89	4.52	26.28	2.14	108.42	1.28	291.54
	(2.7)	(3.0)	(114.7)	(1.4)	(51.2)	(1.5)	(84.1)
72	198.43	4.60	24.04	2.22	101.76	1.24	287.18
	(3.3)	(2.8)	(117.5)	(1.6)	(46.0)	(1.5)	(83.0)
73	195.91	4.82	24.96	2.55	90.29	1.21	288.40
	(3.7)	(3.2)	(139.8)	(1.7)	(71.4)	(1.5)	(93.9)
74	193.25	4.67	24.38	2.79	76.52	1.10	292.92
	(3.8)	(3.3)	(142.7)	(1.8)	(82.1)	(1.5)	(97.7)
75	190.63	4.11	18.61	2.99	59.52	1.24	317.20
	(3.8)	(2.6)	(144.0)	(2.0)	(43.7)	(1.2)	(109.7)
76	189.46	3.29	13.43	3.72	50.70	1.00	322.77
	(4.4)	(3.0)	(135.0)	(1.8)	(35.8)	(1.3)	(106.1)
77	188.86	2.66	12.36	3.82	48.00	.56	297.65
	(4.1)	(2.1)	(131.9)	(2.4)	(46.8)	(1.7)	(103.5)
78	186.09	2.13	18.54	3.97	34.57	.84	277.21
	(5.1)	(2.8)	(125.6)	(3.1)	(120.3)	(1.6)	(110.6)
79	183.09	3.25	19.29	3.03	20.69	.87	241.27
	(6.4)	(4.4)	(105.8)	(2.9)	(131.6)	(1.7)	(105.8)
80	183.16	3.11	29.96	2.86	355.42	.27	314.44
	(6.7)	(3.5)	(124.0)	(2.5)	(140.2)	(1.6)	(113.1)

It may be noted that the reference atmosphere (temperature) presented in Table 1 does not contain the contributions from the quasi-biennial oscillation (QBO). As discussed by Sasi and Krishna Murthy[21], QBO in temperature is significant in the height range 15-42 km. Above 42 km, QBO is weak and irregular. In the reference atmosphere (temperature) given in Table 1, QBO is not included mainly because of its variability in period and amplitude from cycle to cycle. Thus for the reference atmosphere (temperature) given in Table 1, QBO along with any other random fluctuations will add to the variance or standard deviation. This aspect is discussed in the following section.

4 Reference model

Using the mean values of $\bar{A}_0$, $\bar{A}_1$, $\bar{A}_2$, $\bar{A}_3$, $\bar{\phi}_1$, $\bar{\phi}_2$ and $\bar{\phi}_3$ given in Table 1 and Eq. (1), monthly mean values of temperature at every one kilometre from surface to 80 km can be generated. Once the thermal structure of the atmosphere up to 80 km is known, the pressure and density distributions may be calculated using hydrostatic equation [Eq. (2)] and perfect gas law [Eq. (3)] given below if the monthly mean surface pressure $\bar{p}_0$ is known.

$$\bar{p}(z) = \bar{p}_0 \exp\left[-\int_0^z \left(\frac{g}{RT}\right) dz\right] \quad \ldots(2)$$

where

$\bar{p}(z)$ Pressure (monthly mean) at a height z
g Acceleration due to gravity
R Gas constant for dry air assumed to be constant up to 80 km
$\bar{T}$ Monthly mean temperature

$$\bar{p} = \bar{\rho} R \bar{T} \quad \ldots(3)$$

where $\bar{\rho}$ is the monthly mean density.

Thus from the monthly temperature height profile, the pressure and density distributions can be obtained under hydrostatic approximation and ideal gas law assumption.

5 Year-to-year variations of A_0, A_1, A_2, A_3, ϕ_1, ϕ_2 and ϕ_3

The year-to-year variations of A_0, A_1, A_2, ... were determined in the following way. After determining the spectrum of temperature data using FFT, the contributions from QBO (16-48 months) were removed and the residuals obtained for 192 months. These residuals were then divided into 16 segments (each comprising 12 monthly means) and for each segment the annual mean and the annual, semiannual and terannual amplitudes and phases were determined using FFT in the 0-80 km region.

Figure 3(a-c) shows the plots of annual mean temperature (A_0) as a function of time at three representative heights, namely, 17, 40 and 70 km respectively. It is seen from the figure that significant variation of the annual mean temperature exists over the 16-year period from 1971 to 1986. The temperature (A_0) at 17 km [Fig. 3(a)] shows a minimum value in 1976, near sunspot minimum

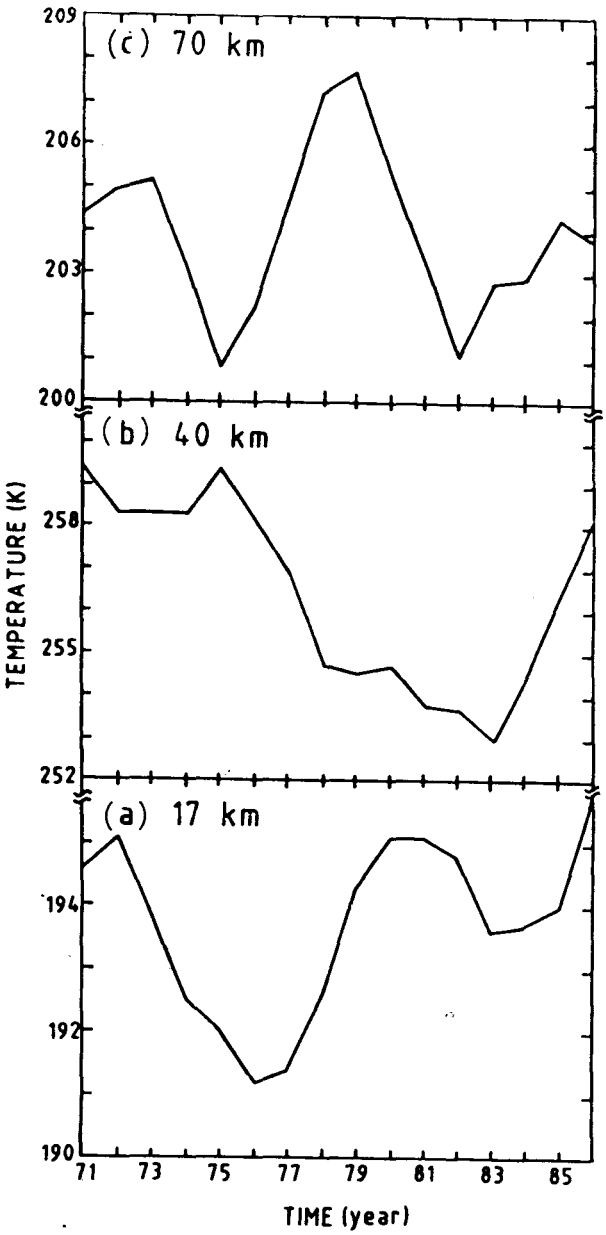

Fig. 3—Year-to-year variation of annual mean temperature at Trivandrum (8.5°N, 77°E) for the period 1971-86 at (a) 17 km, (b) 40 km, and (c) 70 km heights.

and a maximum value in 1980-81, near sunspot maximum, and again a maximum value during the sunspot minimum period 1985-86. The temperature variation at 70 km [Fig. 3(c)] shows that temperature is minimum in 1975, maximum in 1979 and another minimum in 1982. Therefore no clear solar cycle correlation can be seen in temperature variations at 17 and 70 km heights. At 40 km [Fig. 3(b)], temperature variation shows a maximum in 1975, a minimum in 1982-83 and a maximum in 1986. Apparently temperature and solar cycle variations are not correlated at 40 km. The long-term variation of temperature has not been pursued further in the present investigation. However, it is interesting to note that the long-term variation of annual mean temperature has a large range of 5-7 K.

There are variations in annual, semiannual and terannual oscillations also. The year-to-year variations of A_0, A_1, A_2, A_3, ... ϕ_3 were determined from the values of these parameters obtained for each of them for the 16-year period. The height profiles of the 16-year mean of these parameters along with their standard deviations (σ), representing the year-to-year variations, are given in Figs 4-7. In Table 1, along with the mean values of these parameters, the values of σ are also given in parentheses. Figure 4 gives the height variation of the annual mean temperature (A_0). The amplitude (A_1) and phase (ϕ_1) of the annual oscillation (AO) in temperature are given in Fig. 5. The zero of the phase (ϕ_1) of AO corresponds to the month of December. The amplitude (A_2) and phase (ϕ_2) of the semiannual oscillation (SAO) in temperature are given in Fig. 6. The zero of the SAO phase (ϕ_2) corresponds to the months of December and June. Figure 7 shows the amplitude (A_3) and phase (ϕ_3) of the terannual oscillation (TAO) in temperature. The zero of the TAO phase (ϕ_3) corresponds to the months of December, April and August. Further, 30° corresponds to 1 month for AO, 60° for SAO and 90° for TAO respectively. In these figures the solid curve represents the 16-year mean values and the dashed curve mean $\pm\sigma$. It is seen from these figures that there are significant year-to-year variations in these parameters.

A comparative study of the 16-year mean amplitudes and phases of AO, SAO, and TAO over Trivandrum with those obtained by Nastrom and Belmont[22] for 10°N latitude (hereinafter designat-

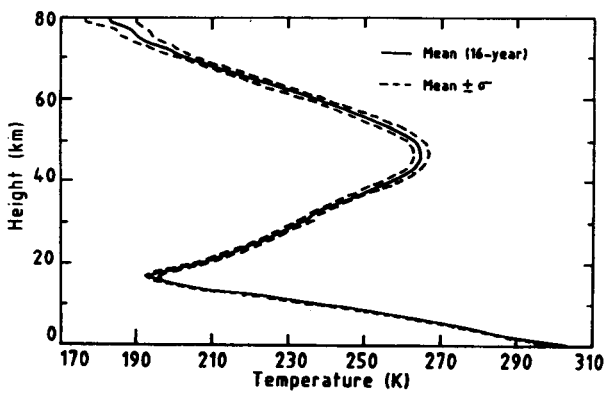

Fig. 4—16-year average annual mean temperature (solid curve) at Trivandrum (8.5°N, 77°E) and mean ± standard deviations (dashed curves) representing year-to-year variations.

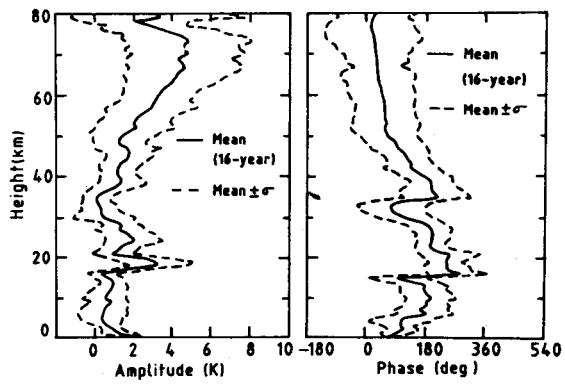

Fig. 5—Amplitude and phase of annual oscillation (AO) in temperature at Trivandrum (8.5°N, 77°E). 16-year mean values are shown by solid curves and the mean ± standard deviations representing year-to-year variations by dashed curves.

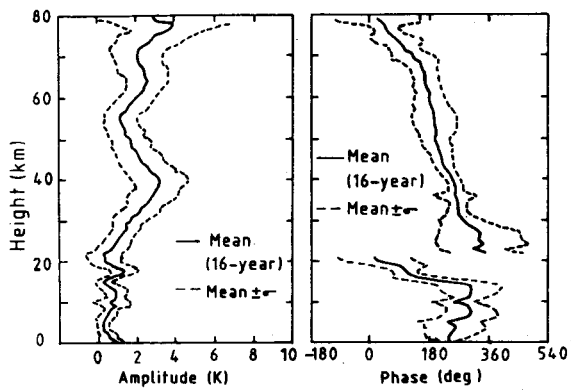

Fig. 6—Same as Fig. 5, but for semiannual oscillation (SAO).

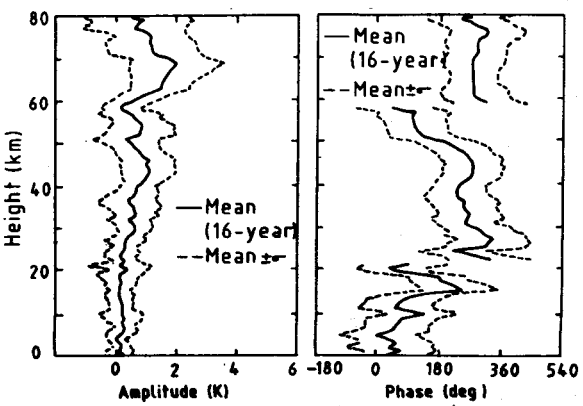

Fig. 7—Same as Fig. 5, but for terannual oscillation (TAO).

ed as NB 10) shows that the mean values for Trivandrum generally agree with those for NB 10. NB 10 values are based on rocket-measured temperature data over Kwajalein (8°N, 167°W) for a period of about 10 years and over Fort Sherman (9°N, 80°W) for a period of about 7 years. The amplitudes and phases of NB 10 cover the height range 20-65 km.

The AO amplitude (A_1) (Fig. 5) at Trivandrum is about 2 K near 20 km and it decreases with increase in height and reaches a minimum near 35 km and thereafter it increases with height to a value of about 4 K at 65 km. NB 10 also shows a similar behaviour with an amplitude of about 2 K at 20 km, a decrease with height reaching a minimum in the 35-40 km region and thereafter an increase in amplitude with height reaching a value of 4-5 K at 65 km. The AO phase (ϕ_1) at Trivandrum shows a downward propagation of phase (time of maximum temperature) in the height region 65-20 km and the phases occur in January at 65 km and in August at 20 km with a small region of upward phase propagation near 30 km. NB 10 also shows a very similar phase propagation with the phases occurring in December-January at 65 km and in August at 20 km.

The SAO amplitude (A_2) (Fig. 6) at Trivandrum shows a broad peak of about 3 K at around 40 km and a minimum of about 1 K at 55 km and then it increases with height to reach a value of about 2.5 K near 65 km. The SAO amplitude for NB 10 also shows a broad peak of about 3 K around 40 km and a minimum of about 1 K between 50 and 55 km and an increase with height to reach a value >2 K at 65 km. The SAO phase (ϕ_2) at Trivandrum shows a downward phase propagation from 65 to 20 km. NB 10 also shows a similar feature in the 65-20 km region. The absolute values of the phases for Trivandrum and NB 10 are the same in the 65-40 km. At 30 and 20 km a difference of about 1 month exists between the SAO phases for Trivandrum and NB 10.

The amplitude of TAO (A_3) (Fig. 7) at Trivandrum is extremely small (<1 K) at most of the heights between 65 and 20 km. NB 10 also shows a similar pattern. The TAO phase (ϕ_3) at Trivandrum and that for NB 10 show downward phase propagation in the 60-35 km height region, with the absolute phase values close to each other (± 1 month).

6 Limitations of the reference model temperature distribution

In section 3, it was shown that $\bar{A}_0$, $\bar{A}_1$, $\bar{A}_2$, ..., $\bar{\phi}_3$, from which the monthly mean temperatures were derived, are having considerable year-to-year variations. In order to see how close the generated monthly mean temperatures are to the observed monthly mean values, the following test was carried out. First the root mean square (r.m.s.) differences between the model (derived from $\bar{A}_0$, $\bar{A}_1$, ..., $\bar{\phi}_3$) monthly mean temperatures and observed monthly mean temperatures (192 months) were computed at every one kilometre height. The vertical distribution of these r.m.s. differences is shown in Fig. 8 (dotted curve). In Fig. 8, the r.m.s. errors in monthly mean temperatrues are also shown (solid curve). It is seen that the r.m.s. differences between the model and the observed temperatures are significantly larger than the measurement errors in the monthly means. This essentially means that the observed temperatures contain variations other than those (long-term mean and mean AO, SAO and TAO) considered for obtaining the model values. These other variations are those having periods longer than 12 months and shorter than 4 months and also year-to-year (or cycle-to-cycle) variations of AO, SAO and TAO.

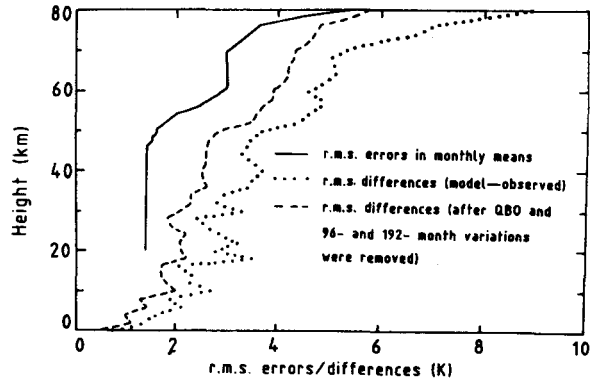
Height (km)
r.m.s. errors/differences (K)
r.m.s. errors in monthly means
r.m.s. differences (model—observed)
r.m.s. differences (after QBO and 96- and 192- month variations were removed)

Fig. 8—Plots of r.m.s. errors in monthly mean temperatures (solid curve), r.m.s. differences between reference model and observed monthly mean temperatures (dotted curve) and r.m.s. differences between the two after long-term variations (QBO and 192 and 96 months) are removed (dashed curve).

One long-term variation, with period more than 12 months, is QBO. Sasi and Krishna Murthy[21] have shown that QBO amplitudes in temperature in the 15-42 km region over Trivandrum are very significant and have values of the order of 2 K. At certain heights the QBO amplitudes reach a value of about 3.5 K. The QBO amplitudes are of the same order as the AO and SAO amplitudes. In addition to the QBO variations, other longer-term variations are also present in temperature as shown in Fig. 3(a-c). Similar longer-term variations (probably related to the 11-year solar cycle) are reported in literature[13,23-26] in the ob-

served temperatures in the tropical middle atmosphere. In the spectrum analysis of the 192 monthly mean temperatures, if any spectral peaks are present corresponding to the period of 11 years, most of the power in the peaks will get distributed in the spectral components corresponding to 96 and 192 months.

The contributions from QBO (16-48 months) and the 96- and 192-month components were subtracted from the observed monthly means and again the r.m.s. differences between the observed and model temperatures were computed. These r.m.s. differences are also shown in Fig. 8 (dashed curve). It is seen that r.m.s. differences are significantly reduced at most of the heights when QBO, 96- and 192-month variations are removed from the observed monthly mean temperatures.

In addition to the long-term variations mentioned above, there are variations of atmospheric temperatures on time scales of less than a month. These may be primarily categorized into two. The first is the category of short-term variations produced by the diurnal and semidiurnal tides forced by the diurnal heating of O_3 and H_2O by solar radiations. These become important above about 25 km. Sasi and Krishna Murthy[27] have shown that diurnal and semidiurnal amplitudes of temperature in the mesosphere reach a maximum value of 8-9 K. Importance of these tidal variations will be further discussed in the next section. The second is the category of random variations about the monthly means. These random variations may be represented by the standard deviations of the observed (weekly) temperatures about the monthly mean temperatures and may be assumed to have a Gaussian distribution. These standard deviations are given in Table 2 for the months of January, April, July and October.

7 Comparisons with CIRA 1986

The monthly mean reference model of temperatures obtained from the data over Trivandrum from 1971 to 1986 is compared with the reference atmosphere (for 10°N) taken from CIRA 1986 (Ref. 5). The results of the comparison are shown in Fig. 9 for the months of January, April, July and October. Here the reference atmosphere over Trinvandrum is taken as the reference. The comparisons are shown at every 5-km height.

It is seen from Fig. 9 that below 25 km height the differences between the reference atmosphere over Trivandrum (hereinafter designated as T_{ref}) and the CIRA 1986 for 10°N (hereinafter referred to as CIRA 86) are small, the maximum difference being about 2.5 K. At 30 km the differences

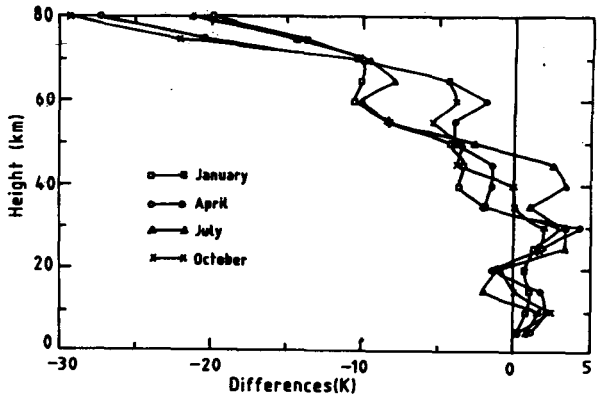

Fig. 9—Differences between monthly mean temperatures (T_{ref} − CIRA 86) for January, April, July and October.

in (T_{ref} − CIRA 86) show a peak, T_{ref} being warmer and the maximum difference reaching a value of about 4 K during April. In the 35 to 50 km height region the differences in (T_{ref} − CIRA 86) are lying in the range 1-4 K.

Above 55 km, T_{ref} is colder than CIRA 86, the maximum difference (~ 30 K) reaching in the upper mesosphere (80 km). A similar finding was reported earlier by Koshelkov[28] who showed that the rocketsonde data for 10°S latitude were colder than reference atmosphere proposed by Barnett and Corney[3] by about 14 K in the 75-80 km region. The large differences between T_{ref} and CIRA 86 might originate from different sources. The measurement techniques adopted in temperature measurements by rocketsonde and satellite-based instrument may be one of the sources of differences in (T_{ref} − CIRA 86). The meteorological rocketsonde provides *in situ* measurements of atmospheric temperature with a vertical resolution of 1-2 km. Satellites, on the other hand, measure the temperature fields in the stratosphere and mesosphere by remote sensing techniques and these temperatures are, generally, derived from radiance measurements by satellite-borne infrared radiometers. From the radiance data the vertical temperature profile is retrieved either through inversion of the Planck's radiative equation or by regression techniques[29]. For both the techniques a reference vertical temperature profile (provided by radiosonde and rocketsonde measurements) is required for the temperature retrieval from the radiance data and the height resolution obtained is 3-12 km (Ref. 30). Barnett and Corney[30] have reported temperature differences of maximum of about 8 K at about 54 km and about 5 K at lower levels between the rocketsonde and satellite measurements over Fort Churchill (59°N, 94°W)

Table 2—Standard deviations of the temperatures (K) about the monthly means at Trivandrum (8.5°N, 77°E) for the months of January, April, July and October

Height km	Jan.	Apr.	July	Oct.	Height km	Jan.	Apr.	July	Oct.
0	1.8	2.5	2.7	2.1	41	3.8	2.9	4.4	2.6
1	1.4	1.2	1.5	1.5	42	4.1	2.8	3.8	2.8
2	1.8	1.1	1.5	1.8	43	4.5	2.7	3.8	2.3
3	1.3	1.4	1.4	1.0	44	4.6	3.0	3.8	2.4
4	1.6	1.3	1.4	1.3	45	4.4	2.9	3.9	2.8
5	1.7	1.2	1.6	1.7	46	4.4	2.8	3.2	3.1
6	1.8	1.2	1.4	1.5	47	4.1	2.9	3.3	3.6
7	1.4	1.2	1.4	1.6	48	3.8	3.2	3.2	3.5
8	1.6	1.8	1.5	1.5	49	3.5	3.0	3.4	3.2
9	1.3	2.2	1.8	1.4	50	3.8	3.1	3.6	3.2
10	1.4	1.8	1.9	1.7	51	4.0	3.1	3.6	3.0
11	1.5	2.0	2.1	1.6	52	4.2	2.9	3.6	2.9
12	1.5	2.1	1.9	1.8	53	4.5	3.1	3.6	2.7
13	1.9	2.0	1.8	1.8	54	4.4	3.5	3.9	3.0
14	2.1	1.9	1.9	2.0	55	4.9	4.0	4.2	3.8
15	1.8	2.0	1.8	2.0	56	5.5	4.3	4.8	4.3
16	2.2	2.1	2.4	2.4	57	6.0	4.6	4.9	4.7
17	1.9	2.3	2.1	2.4	58	6.3	4.6	5.3	4.7
18	2.3	2.7	2.0	2.3	59	6.8	5.0	5.3	4.8
19	2.2	2.5	1.9	1.9	60	6.9	5.2	5.6	5.2
20	2.0	2.2	2.1	2.3	61	7.0	5.4	5.7	5.3
21	2.1	2.2	2.2	2.5	62	7.3	5.8	5.7	5.2
22	2.3	1.8	2.0	1.9	63	7.4	5.9	5.8	5.2
23	2.4	1.9	2.1	1.9	64	7.6	6.1	5.9	4.8
24	3.0	2.1	2.6	1.8	65	7.2	6.3	5.8	5.0
25	2.8	2.3	2.3	2.0	66	6.9	6.2	5.7	5.3
26	2.9	2.3	2.0	2.1	67	6.5	6.1	5.7	4.8
27	3.0	2.5	2.3	2.5	68	6.3	6.0	5.6	5.0
28	2.7	2.2	2.4	2.5	69	6.5	5.9	8.5	4.6
29	2.6	2.8	2.2	2.2	70	6.7	5.8	6.0	5.1
30	2.9	2.3	2.2	2.1	71	6.4	6.2	6.1	4.9
31	3.1	2.3	2.8	2.5	72	6.0	6.2	5.4	4.4
32	2.9	2.5	2.6	2.5	73	5.6	5.8	4.9	4.3
33	2.9	2.7	2.6	2.5	74	6.1	6.1	4.9	4.4
34	3.1	2.5	3.2	2.8	75	6.0	5.8	4.9	4.3
35	3.3	2.3	3.2	2.6	76	6.2	5.0	5.3	4.6
36	3.4	2.5	3.4	2.8	77	6.9	5.8	6.3	4.5
37	3.4	2.6	3.5	2.6	78	8.2	6.2	6.8	6.4
38	3.1	2.4	3.3	1.8	79	10.0	7.9	8.9	7.8
39	3.7	2.7	3.3	2.2	80	11.5	8.5	9.7	9.5
40	4.0	2.8	3.9	2.9					

and Volgograd (49°N, 44°E). Thus the large differences in (T_{ref} − CIRA 86) in the mesosphere shown in Fig. 9 might arise partly from the difference in measurement techniques.

Another source of these differences in (T_{ref} − CIRA 86) may be the large longitudinal variation of temperature in the equatorial mesosphere. Recently, Clancy and Rusch[13] have reported that longitudinal variation as large as 20 K can occur in the upper mesosphere in the equatorial region and for this study they have utilized ultraviolet Limb radiance data from the Solar Mesosphere Explorer (SME) satellite. The temperature profiles of CIRA 86 are the zonal mean profiles, whereas T_{ref} temperature profiles are for the 77°E longitude. Thus the longitudinal variation of the

thermal structure can account for some of the differences in (T_{ref} − CIRA 86) in the mesosphere as shown in Fig. 9.

As discussed by Sasi and Krishna Murthy[27], large diurnal tidal amplitudes exist in the middle atmospheric temperatures over Trivandrum. The rocket (M-100/M-100B) launchings were done at fixed times on Wednesdays (at 2000 hrs IST from 1971 to 1975, at 1930 hrs IST from 1976 to 1984, and at 1710 hrs IST from 1984 to 1986). This introduced a bias in the rocket-measured temperatures, especially in the mesosphere where maximum diurnal amplitudes of 8-9 K exist. The CIRA 86 data on the other hand consist of temperature data averaged in longitude as well as in local time (over several orbits). Thus the influence of tides can also partly account for the differences in (T_{ref} − CIRA 86) seen in the mesosphere.

Further, T_{ref} consists of only a mean temperature and annual, semiannual and terannual oscillations superimposed on the mean value, and the QBO and solar cycle related variations are treated as perturbations on the monthly mean values of T_{ref}. But CIRA 86 profiles are based on the data from January 1973 to July 1978 and include the effects of QBO and solar cycle related variations also. The QBO and solar cycle variations in the mesosphere are in the range 1.5-5 K. The data base for the CIRA 86 profiles belongs to the ascending phase of the solar cycle and this can also influence the CIRA 86 temperature profiles.

Thus most of the differences between T_{ref} and CIRA 86 temperature profiles may be attributed to longitudinal variability, differences between rocketsonde and satellite measurements, tidal influences, and QBO and solar cycle related variations.

8 Summary and conclusions

(1) A reference atmosphere (temperature, pressure and density) in the height range 0-80 km, applicable for Indian equatorial zone, has been developed. The monthly mean profiles of the atmospheric parameters can be generated using a set of seven coefficients [a long-term annual mean, amplitudes and phases of annual oscillation (AO), semiannual oscillation (SAO), and terannual oscillation (TAO) of temperature] at every kilometre height. These coefficients have been derived using temperature data obtained from *in situ* measurements by meteorological balloons and M-100/M-100B rockets at Trivandrum (8.5°N, 77°E) from 1971 to 1986.

(2) The set of seven coefficients used for generating the reference model atmosphere shows significant year-to-year variation over the 16-year period from 1971 to 1986. However, the mean values of the amplitudes and phases of AO, SAO and TAO show very good agreement with the values reported by Nastrom and Belmont[22] in the 20-65 km region.

(3) A comparative study of this reference model atmosphere with the recent CIRA 86 reference atmosphere[5], based on satellite data, shows that very significant differences exist between the two in the mesosphere. These differences might be due to (i) longitudinal asymmetry of the thermal structure in the equatorial mesosphere, (ii) long-term variations such as QBO and solar cycle related variations, (iii) short-term variations such as diurnal tides, and (iv) differences between rocketsonde and satellite measurements of temperature.

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